Received: 31 March 2023 | Revised: 28 August 2023 | Accepted: 11 September 2023

DOI: 10.1002/dad2.12484

Alzheimer's & Dementia
Diagnosis, Assessment & Disease Monitoring

RESEARCH ARTICLE

Neighborhood greenspace and neighborhood income associated with white matter grade worsening: Cardiovascular Health Study

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Funding information
Alzheimer's Association, Grant/Award Number: AARG-21-850963; NIH/NIA, Grant/Award Numbers: K01AG063895, R21AG075291, 3R01AG049970-04S1, R01AG072634, R01AG040211, R01NS101483, R01AG023629; NHLBI, Grant/Award Numbers: U01HL130114, U01HL080295

Abstract

INTRODUCTION: We examined whether a combined measure of neighborhood greenspace and neighborhood median income was associated with white matter hyperintensity (WMH) and ventricle size changes.

METHODS: The sample included 1260 cognitively normal $\geq$ 65-year-olds with two magnetic resonance images (MRI; $\approx$ 5 years apart). WMH and ventricular size were graded from 0 (least) to 9 (most) abnormal (worsening = increase of $\geq$1 grade from initial to follow-up MRI scans). The four-category neighborhood greenspace–income measure was based on median neighborhood greenspace and income values at initial MRI. Multivariable logistic regression tested associations between neighborhood greenspace–income and MRI measures (worsening vs. not).

RESULTS: White matter grade worsening was more likely for those in lower greenspace–lower income neighborhoods than higher greenspace–higher income neighborhoods (odds ratio = 1.73; 95% confidence interval = 1.19–2.51).

DISCUSSION: The combination of lower neighborhood income and lower greenspace may be a risk factor for worsening white matter grade on MRI. However, findings need to be replicated in more diverse cohorts.

KEYWORDS
built environment, green space, magnetic resonance imaging, neighborhood, socioeconomic status

HIGHLIGHTS

- Population-based cohort of older adults (≥ 65 years) with greenspace and MRI data
- Combined measure of neighborhood greenspace and neighborhood income at initial MRI
- MRI outcomes included white matter hyperintensities (WMH) and ventricular size
- Longitudinal change in MRI outcomes measured approximately 5 years apart
- Worsening WMH over time more likely for lower greenspace-lower income neighborhoods

1 | BACKGROUND

Social determinants of health (SDOH), the "conditions in the places where people live, learn, work, and play that affect a wide range of health and quality-of-life risks and outcomes,"[1] are associated with the modifiable risk factors (e.g., hypertension, depression, physical inactivity) responsible for 40% of dementias.[2–6] Targeting SDOH through individual-, community-, and policy-level interventions could reduce these risk factors, thus improving brain health and reducing risk of Alzheimer's disease and related dementias (ADRD).[7]

Residential neighborhoods, a SDOH, become increasingly important with age and the associated shrinking social networks, retirement, reduced driving or mobility, and medical issues.[8,9] Depression, physical inactivity, and diabetes increase dementia risk and are associated with neighborhood exposures in older adults.[10–12] Neighborhood socioeconomic status (NSES) is a neighborhood exposure studied frequently, with moderate evidence for associations with ADRD outcomes.[13] For instance, middle- to older-age adults in the most disadvantaged neighborhoods demonstrated cortical thinning in Alzheimer's disease (AD) regions of interest (ROI) and greater longitudinal cognitive decline,[14] and 4.1% lower hippocampal volume.[15]

Built environments (physical residential, work, and school environments) influence behaviors and environmental exposures related to brain health and ADRD. Specifically, neighborhood greenspaces such as parks and tree canopy have been beneficially associated with modifiable risk factors (e.g., physical activity and diabetes) and reduced ADRD risk and cognitive impairment.[16–18] While evidence is accumulating for associations between neighborhood greenspaces and better brain health,[19] most studies of older adults have focused on cognitive outcomes. Cognitive test results can vary by factors unrelated to underlying neurological conditions, such as differences in education, racialized/ethnic group, primary language, and health status.[20] Studies using biomarkers such as brain magnetic resonance imaging (MRI) may provide less biased evidence for associations between greenspace and brain health.

Limited studies have investigated associations between greenspace and MRI outcomes.[21–27] Living in greener areas has been associated with greater cortical thickness in AD ROI[22–24] and living in more forested areas has been associated with greater amygdala integrity.[25] In addition, greater neighborhood greenspace has been associated with greater gray matter volume (e.g., left middle frontal lobe and temporal pole),[27] and borderline positively associated with ventricle grade.[21] Despite growing evidence, prior studies were cross-sectional and lacked consideration of interactions between greenspace and NSES.

Research is needed on the independent and combined influence of greenspace and NSES on health. Understanding this interaction is crucial to inform interventions targeting disadvantaged neighborhoods. Our study examined associations of a combined neighborhood greenspace and NSES measure with 5-year change in white matter and ventricle grade among older adults. Ventricular enlargement (brain atrophy) and white matter hyperintensities (e.g., demyelination and axonal degeneration), as evidenced by white matter and ventricle grade scores, are brain health markers that predict dementia risk and correlate with symptomatic/neuropathological ADRD and later stages of disease.[28–31] Thus, these MRI biomarkers are tied to future ADRD risk and ADRD prevention. We hypothesized that individuals in neighborhoods with less greenspace and lower NSES would have greater worsening of these measures over time.

RESEARCH IN CONTEXT

1. **Systematic review**: The authors reviewed PubMed and Web of Science for published articles on associations between neighborhood greenspaces and neighborhood socioeconomic status (NSES) with brain imaging outcomes. The pertinent citations are cited.
2. **Interpretation**: This study adds to the extant literature by investigating associations between a combined measure of neighborhood greenspace and NSES and longitudinal change in magnetic resonance imaging (MRI) outcomes among older adults. Our findings suggest that the combination of lower neighborhood income and lower greenspace may be a novel risk factor for worsening white matter grade on MRI.
3. **Future directions**: These preliminary findings point to avenues for future research, including studies that focus on minoritized groups and neighborhoods, use mixed methods, and investigate the impact of greenspace quality, time spent in greenspaces, and refined NSES measures on longitudinal brain imaging outcomes.

2 | METHODS

2.1 | Sample

The population-based Cardiovascular Health Study (CHS) recruited ≥ 65-year-olds from Forsyth County, North Carolina; Sacramento County, California; Pittsburgh, Pennsylvania; and Washington County, Maryland. Most (n = 5201) were enrolled in 1989 and 1990, with 687 predominantly Black participants enrolled in 1992 and 1993 using the same recruitment methods.[32] Annual clinic visits (until 1999) assessed comorbidities, risk factors, and subclinical cardiovascular disease. Detailed CHS procedures are elsewhere and participants provided informed consent.[33] We restricted to participants with (1) neighborhood measures at initial MRI, (2) two MRIs (1991–1994 and 1997–1999), and (3) no cognitive impairment/dementia at initial MRI (i.e., dementia International Classification of Disease 9th Edition codes from hospital/outpatient visits, dementia medications, cognitive screening suggested significant decline, or proxy respondent due to cognitive difficulty).

2.2 | MRIs

Sites used standardized MRI protocols, with three sites using 1.5T GE or Picker scanners and one using a 0.35T Toshiba scanner.[34–37] Neuroradiologists blinded to diagnosis assessed ventricular size from T1-weighted images and white matter hyperintensity (WMH) burden from spin-density weighted axial images (graded 0 [least] to 9 [most] abnormal). Side-by-side reads by two raters provided ventricle and white matter grade change measures between initial and follow-up scans (intrareader reliability: $\kappa = 0.69$; inter-reader reliability: $\kappa = 0.36$[37]). Few had longitudinal change in scores of > 1 point; thus, we dichotomized change as worsening (> 0) or not (≤0; 2 had white matter grade improvement, 14 had ventricle grade improvement).

2.3 | Neighborhood characteristics

Proportion greenspace and forest cover (deciduous, evergreen, or mixed) were derived for 1-km circular buffers around residences using the National Land Cover Database (NLCD; 1992, 2001).[38] Using satellite imagery, the NLCD classifies land and surface uses/types (e.g., developed land and forest).[39] Annual measures were calculated from a linear interpolation of NLCD values between 1992 and 2001; we carried the 1992 value backward for earlier years. Global greenspace was based on all land types corresponding to vegetation, and measures accounted for address changes during follow-up.

Neighborhood median household income and population density (people/km^2) for the 1-km buffers were derived from the Longitudinal Tract Database (1990, 2000).[40] Weighted average values were calculated for each buffer based on proportion of Census tract covered. Annual neighborhood income and population density were calculated from a linear interpolation of 1990 and 2000 values. We used neighborhood greenspace, income, and population density values from the initial MRI.

The primary exposure was a neighborhood typology based on greenspace and neighborhood income. This was determined a priori to be consistent with definitions used by fields (e.g., urban planning) that influence neighborhood environments and understand them holistically. Neighborhood typologies consider intersecting and defining traits of neighborhoods recognized by researchers and lay people (e.g., "minority urban").[41,42] To this end, we dichotomized at the medians (greenspace: ≤ 37% vs. > 37%; neighborhood income: ≤ $56,267% vs. > $56,267%) to create our four-category neighborhood typology: lower greenspace–lower income, lower greenspace–higher income, higher greenspace–lower income, and higher greenspace–higher income (reference). Lacking available standardized (and clinically significant) cut points, we chose median cut points to maximum sample size in each category.

2.4 | Participant characteristics

Baseline demographics included age (initial MRI), sex, self-identified racialized group (White, Black, American Indian/Alaska Native, Asian/Pacific Islander, other), self-identified Hispanic ethnicity, participant's income (wages, retirement savings, etc.; 8-category measure grouped by tertile: < $12,000/year, $12–$24,999/year, ≥ $25,000/year), education (< high school degree, high school degree, some college/vocational school, college degree or beyond), and marital status (married vs. never/divorced/separated). For multivariable analyses, categorical/dummy variables were created for racialized groups (non-White vs. White; did not consider Hispanic/Latino ethnicity due to small sample) and education (higher and lower education vs. high school degree). Apolipoprotein E (*APOE*) genotype was dichotomized as carrier (≥ 1 ε4 allele) versus non-carrier (no ε4 alleles).[43]

Health variables included body mass index (kg/m^2), total kilocalories (kcal) of self-reported physical activity/week,[44] blocks walked/week, and smoking status (current, former, never) from visit closest to initial MRI (time between visit and MRI: mean = 92 days; standard deviation [SD] = 91), as well as pack-years smoked at baseline. Comorbidities from visit closest to initial MRI included hypertension (≥ 140 mmg systolic, ≥ 90 mm diastolic, or self-reported diagnosis plus anti-hypertensive use), depressive symptoms (10-item Center for Epidemiological Studies Depression scale[45]), self-reported/treated arthritis, and diabetes (high glucose or medication use). Participant-reported cardiovascular disease (cardiac bypass, congestive heart failure, heart attack, coronary heart disease, angina) and cerebrovascular disease (stroke, transient ischemic attack) at initial MRI were confirmed via medical record adjudication.[46,47] The modified Mini-Mental State Examination (3MSE) measured global cognition (0 [worst] to 100 [best]).

2.5 | Analyses

We describe characteristics (e.g., means and SDs) for the total sample and stratified by neighborhood greenspace–income categories. Unadjusted linear or logistic regression tested differences in participant characteristics by greenspace–income group. Statistical significance included $P < 0.05$.

Multivariable logistic regression using generalized estimating equations (clustering by US Census tract) tested associations between dichotomized neighborhood greenspace and neighborhood income variables (separately) and dichotomous measures of worsening white matter and ventricle grade from initial to follow-up MRI. These analyses determined if neighborhood greenspace and neighborhood income were independently associated with the MRI outcomes. Models first controlled for demographics (age, sex, race, income, education, marital status), population density, site, and time between initial and follow-up MRI (a priori confounders). We then additionally controlled for health behaviors (ever smoked, physical activity/week), comorbidities (hypertension, arthritis, diabetes, cardiovascular and cerebrovascular disease), and baseline ventricle or white matter grade (depending on model). Models described above were repeated replacing the individual neighborhood variables with the four-category neighborhood greenspace–income measure. A neighborhood greenspace × neighborhood income interaction term was tested in fully adjusted models.

Given the importance of racialization as a social determinant of ADRD,[48] we attempted to subset multivariable models to assess whether exposures had a stronger influence on MRI outcomes among Black participants. Models did not converge due to insufficient sample size and running models without clustering was ill advised. Thus, race-stratified analyses are future priorities.

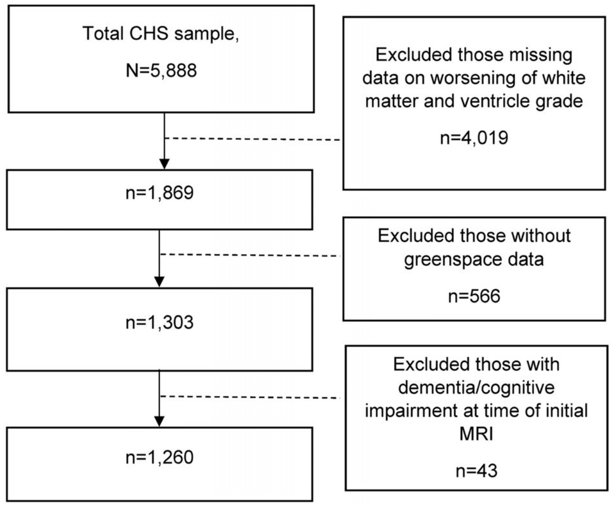

FIGURE 1 Sample size flow diagram. CHS, Cardiovascular Health Study; MRI, magnetic resonance imaging

As a first sensitivity analysis, we omitted race from multivariable analyses to examine whether this social construct and marker of experienced discrimination was a significant confounder. Second, we examined separate associations for both exposures measured in quartiles, which assessed differing cut points (i.e., quartiles vs. dichotomized at median). Third, focusing on the four-category neighborhood greenspace–income measure, we additionally controlled for ≥ 1 *APOE* ε4 allele because *APOE* genotype may vary geographically[49] and has been associated with our MRI outcomes.[50] Fourth, we removed participants in the top 5% highest or lowest population densities to assess impact of extreme population densities (i.e., lack of overlap of more extreme population densities between lower greenspace–lower income and higher greenspace–higher income). Fifth, we created a composite NSES measure (mean of *z* score–standardized Census tract measures of median household income, percentage with ≤ high school degree, percentage with ≥ 4-year college degree, and percentage living in poverty) to examine whether fully adjusted models using a neighborhood greenspace–NSES measure provided similar findings to the neighborhood greenspace–income measure. The de-identified data precluded linking participants' addresses to established NSES measures (e.g., Area Deprivation Index [ADI]). Post hoc analyses included percentage forest × neighborhood income (both continuous) interaction terms in fully adjusted models to assess whether more specific greenspace (i.e., percentage forest) interacted with neighborhood income.

3 | RESULTS

At initial MRI, participants (n = 1260, Figure 1) were on average 75 years old (SD = 4.4), 57% were women, 12% were Black, 88% were White (0.3% were American Indian/Alaska Native, Asian/Pacific

TABLE 1 Participant characteristics by neighborhood greenspace-neighborhood income groups.

Characteristic[a] (from initial MRI)	Total	Neighborhood greenspace–neighborhood income category: Lower greenspace, lower income	Lower greenspace, higher income[d]	Higher greenspace, lower income[d]	Higher greenspace, higher income[d]
Sample, *n*	1260	393	240	236	391
Age, mean (SD)	74.6 (4.4)	74.8 (4.6)	74.7 (4.5)	74.5 (4.6)	74.4 (4.2)
Female, *n* (%)	720 (57.1%)	222 (56.5%)	132 (55.0%)	134 (56.8%)	232 (59.3%)
Racialized group[e], *n* (%)					
White	1108 (87.9%)	311 (79.1%)[c]	221 (92.1%)	205 (86.9%)[c]	371 (94.9%)
Black	148 (11.8%)	82 (20.9%)[c]	18 (7.5%)	29 (12.3%)[c]	19 (4.9%)
American Indian/Alaska Native	1 (0.1%)	0 (0.0%)[c]	0 (0.0%)	1 (0.4%)[c]	0 (0.0%)
Asian/Pacific Islander	1 (0.1%)	0 (0.0%)[c]	1 (0.4%)	0 (0.0%)[c]	0 (0.0%)
Other	2 (0.2%)	0 (0.0%)[c]	0 (0.0%)	1 (0.4%)[c]	1 (0.3%)
Hispanic ethnicity, *n* (%)	16 (1.3%)	9 (2.3%)[c]	1 (0.4%)	1 (0.4%)	5 (1.3%)
Married, *n* (%)	907 (72.0%)	268 (68.2%)	190 (79.2%)[c]	169 (71.6%)	280 (71.8%)
Income, *n* (%)					
<$12,000/year	226 (19.1%)	76 (20.7%)	27 (12.3%)[c]	45 (20.2%)	78 (20.9%)
$12,000–24,999/year	434 (36.7%)	131 (35.6%)	70 (32.0%)[c]	89 (39.9%)	144 (38.6%)
$≥25,000/year	523 (44.2%)	161 (43.8%)	122 (55.7%)[c]	89 (39.9%)	151 (40.5%)
Education, *n* (%)					
<High school degree	288 (22.9%)	91 (23.2%)[c]	33 (13.8%)[c]	60 (25.4%)	104 (26.6%)
High school degree	359 (28.5%)	99 (25.2%)[c]	65 (27.1%)[c]	87 (36.9%)	108 (27.6%)
Some college/vocational school	302 (24.0%)	90 (22.9%)[c]	74 (30.8%)[c]	44 (18.6%)	94 (24.0%)
≥College degree	311 (24.7%)	113 (28.8%)[c]	58 (28.3%)[c]	45 (19.1%)	85 (21.7%)
≥1 *APOE* ε4 allele, *n* (%)	274 (23.6%)	90 (25.4%)	48 (21.4%)	58 (25.6%)	78 (21.9%)
Time between MRIs, mean (SD)	5.00 (0.76)	4.88 (0.78)[c]	4.93 (0.84)	5.14 (0.71)	5.05 (0.71)
Percent greenspace, mean (SD)	40.4 (28.2)	16.6 (10.1)[c]	17.2 (10.9)[c]	58.8 (17.6)[c]	67.4 (19.2)
Percent forest, mean (SD)	20.1 (19.3)	10.6 (9.7)[c]	8.4 (9.7)[c]	30.5 (20.3)	30.5 (21.4)
Population density[b], mean (SD)	1394 (1296)	2509 (1354)[c]	1761 (918)[c]	709 (737)[c]	453 (495)
Neighborhood income, mean (SD)	59101 (20007)	43373 (9064)[c]	74299 (15701)	47849 (28357)[c]	72374 (19701)

Abbreviations: *APOE*, apolipoprotein E; MRI, magnetic resonance imaging; SD, standard deviation.
[a]Missing data: Hispanic ($n = 2$), married ($n = 1$), income ($n = 77$), *APOE* ($n = 99$).
[b]People/km^2.
[c]Significantly different than "higher greenspace, higher income" group, $P < 0.05$.
[d]Greenspace dichotomized at median of 37%, neighborhood median household income dichotomized at median of $56,267/year.
[e]Black, American Indian/Alaska Native, Asian/Pacific Islander, and those self-identifying as Other were combined for statistical comparison to White participants due to small sample sizes.

Islander, or other), and 1% were Hispanic (Table 1). Forty-nine percent had at least some college education. On average, participants lived in neighborhoods with 40% greenspace (SD = 28%). Mean time between MRIs was 5 years (SD = 0.76). Compared to higher greenspace–higher income neighborhoods, lower greenspace–lower income and higher greenspace–lower income neighborhoods included more participants of Black or other racialized group. Participant counts in each neighborhood greenspace–income category varied by site (Table S1 in supporting information). No distinct patterns emerged in participant distribution by quartile of neighborhood greenspace and neighborhood income, except that in the lowest neighborhood income quartile, more participants represented the bottom two greenspace quartiles (Table S2 in supporting information).

At initial MRI, mean white matter grade score was 1.87 (SD = 1.46) and mean ventricle grade score was 3.31 (SD = 1.21; Table 2). Mean increase from initial to follow-up MRI was 0.35 (SD = 0.59) for white matter grade and 0.31 (SD = 0.51) for ventricle grade. Thirty percent experienced worsening white matter grade and 31% experienced worsening ventricle grade.

Tables 3 and 4 provide multivariable findings. Neighborhood greenspace was not associated with either MRI outcome (although estimates in hypothesized direction; Table 3), whereas living in lower

TABLE 2 Participant health status by neighborhood greenspace–neighborhood income groups.

Characteristic[a] (from initial MRI)	Total $N = 1260$	Neighborhood greenspace-neighborhood income category: Lower greenspace, lower income[b]	Lower greenspace, higher income[b]	Higher greenspace, lower income[b]	Higher greenspace, higher income[b]
Body mass index (kg/m^2), mean (SD)	26.6 (4.2)	26.5 (4.2)	26.4 (4.1)	26.8 (4.0)	26.7 (4.2)
Hypertension, *n* (%)	628 (49.9%)	210 (53.4%)	109 (45.4%)	121 (51.3%)	188 (48.2%)
kcals of PA/week, mean (SD)	1746.8 (1931.7)	1708.2 (1895.2)	1860.2 (1792.1)	1743.0 (2083.9)	1718.0 (1960.2)
Blocks walked per week, mean (SD)	23.5 (44.9)	21.7 (35.6)	31.8 (48.0)[d]	22.3 (56.1)	21.2 (43.3)
Ever smoked, *n* (%)	702 (55.7%)	231 (58.8%)[d]	135 (56.3%)	134 (56.8%)	202 (51.7%)
Smoking pack years, mean (SD)	15.6 (23.5)	16.9 (24.1)	14.4 (24.9)	17.2 (23.5)	13.9 (21.7)
Arthritis, *n* (%)	552 (49.8%)	188 (52.2%)	88 (45.8%)	96 (45.3%)	180 (52.3%)
10-item CES-D scale, mean (SD)	4.6. (4.4)	4.7 (4.5)	4.3 (4.1)	4.9 (4.8)	4.5 (4.1)
Diabetes, *n* (%)	171 (13.9%)	58 (15.0%)	23 (9.8%)	38 (16.2%)	52 (13.8%)
Fasting glucose (mg/dL), mean (SD)	106.4 (33.2)	107.7 (37.2)	103.4 (33.3)	107.1 (31.3)	106.5 (30.1)
Cardiovascular disease, *n* (%)	241 (19.1%)	83 (21.1%)	35 (14.6%)	50 (21.2%)	73 (18.7%)
Stroke/TIA, *n* (%)	65 (5.2%)	15 (3.8%)	12 (5.0%)	12 (5.1%)	26 (6.7%)
3MSE, mean (SD)	92.9 (5.7)	92.1 (6.7)[d]	93.6 (4.9)	93.1 (5.2)	93.2 (5.3)
Initial MRI measure, mean (SD)					
White matter grade	1.87 (1.46)	1.81 (1.50)	1.96 (1.54)	1.85 (1.36)	1.88 (1.42)
Ventricle grade	3.31 (1.21)	3.42 (1.21)	3.36 (1.23)	3.14 (1.25)	3.28 (1.17)
Change from initial to follow-up MRI, mean (SD)					
White matter grade	0.35 (0.59)	0.39 (0.61)	0.30 (0.58)	0.33 (0.56)	0.35 (0.60)
Ventricle grade	0.31 (0.51)	0.29 (0.52)	0.26 (0.48)[d]	0.31 (0.50)	0.35 (0.52)
From initial to follow-up MRI, *n* (%)[c]					
Worsening white matter grade	379 (30.1%)	132 (33.6%)	62 (25.8%)	68 (28.8%)	117 (29.9%)
Worsening ventricle grade	389 (30.9%)	108 (27.5%)[d]	63 (26.3%)[d]	76 (32.2%)	142 (36.3%)

Abbreviations: 3MSE, modified Mini-Mental State Examination; CES-D, Center for Epidemiologic Studies Depression Scale; kcal, kilocalories; MRI, magnetic resonance imaging; PA, physical activity; SD, standard deviation; TIA, transient ischemic attack.

[a]Missing data: kcal ($n = 3$) pack years smoked ($n = 37$), fasting glucose ($n = 6$), hypertension ($n = 1$), arthritis ($n = 152$), diabetes ($n = 25$).

[b]Greenspace dichotomized at median of 37%; neighborhood median household income dichotomized at median of $56,267/year.

[c]Versus no change or improvement from initial to follow-up MRI.

[d]Significantly different than "higher greenspace, higher income" group, $P < 0.05$.

income neighborhoods was associated with greater odds of white matter grade worsening in minimally (odds ratio [OR] = 1.33, 95% confidence interval [CI] = 1.06–1.67) and fully adjusted models (OR = 1.44; 95% CI = 1.12–1.85). Neighborhood income was not associated with ventricle grade in any adjusted models.

Table S3 in supporting information provides unadjusted regression findings for the four-category neighborhood greenspace–income measure. In minimally adjusted models (Table 5), compared to participants in higher greenspace–higher income neighborhoods, those in lower greenspace–lower income neighborhoods had greater odds of white matter grade worsening (OR = 1.60, 95% CI = 1.12–2.30) and those in lower greenspace–higher income neighborhoods had lower odds of ventricle grade worsening (OR = 0.60, 95% CI: 0.38–0.97). In fully adjusted models, only the association between lower greenspace–lower income neighborhoods and white matter grade worsening remained (OR = 1.73; 95% CI = 1.19–2.51). The neighborhood greenspace × neighborhood income interaction terms were not significant in the fully adjusted models for white matter grade ($P = 0.76$) or ventricle grade worsening ($P = 0.12$). No other significant associations were observed.

In sensitivity analyses, omitting race from multivariable models produced similar findings (Tables S4–S6 in supporting information). Dividing neighborhood greenspace into quartiles produced similar, non-significant associations with the MRI outcomes (Table S7 in supporting information). After dividing neighborhood income into quartiles, only the lowest quartile was associated with white matter grade worsening (Table S8 in supporting information). Additionally controlling for ≥ 1 *APOE* ε4 allele and removing extreme population densities resulted in little change in associations (Tables S9 and S10 in supporting information). Models using the neighborhood greenspace–NSES measure provided similar findings as the neighborhood greenspace–income measure. Last, neighborhood

TABLE 3 Adjusted association between dichotomous neighborhood greenspace and dichotomous MRI measures.

MRI outcome (worsening from initial to follow-up MRI)	Neighborhood percentage greenspace[a]	Partially adjusted model[b]		Fully adjusted model[c]	
		OR (95% CI)	*P*-value	OR (95% CI)	*P*-value
White matter grade	Lower (vs. higher) greenspace	1.31 (0.92–1.85)	0.13	1.36 (0.95–1.94)	0.09
Ventricle grade	Lower (vs. higher) greenspace	0.72 (0.49–1.06)	0.19	0.90 (0.64–1.28)	0.58

Abbreviations: CI, confidence interval; MRI, magnetic resonance imaging; OR, odds ratio.
[a]Dichotomized at median of 37%.
[b]Controlling for age, sex, racialized group (non-White vs. White), marital status, income, education, population density, site/clinic, and time between first and second MRI.
[c]Additionally controlling for diabetes, arthritis, hypertension, cardiovascular disease, cerebrovascular disease, ever smoked, kcals of physical activity/week, body mass index, and initial MRI grade on white matter or ventricle as appropriate.

TABLE 4 Adjusted association between neighborhood median income and dichotomous MRI measures.

MRI outcome (worsening from initial to follow-up MRI)	Neighborhood median income[a]	Partially adjusted model[b]		Fully adjusted model[c]	
		OR (95% CI)	*P*-value	OR (95% CI)	*P*-value
White matter grade	Lower (vs. higher) income	1.33 (1.06–1.67)	0.01	1.44 (1.12–1.85)	0.004
Ventricle grade	Lower (vs. higher) income	0.88 (0.65–1.19)	0.39	0.80 (0.61–1.06)	0.12

Abbreviations: CI, confidence interval; MRI, magnetic resonance imaging; OR, odds ratio.
[a]Dichotomized at median of $56,267/year.
[b]Controlling for age, sex, racialized group (non-White vs. White), marital status, income, education, population density, site/clinic, and time between first and second MRI.
[c]Additionally controlling for diabetes, arthritis, hypertension, cardiovascular disease, cerebrovascular disease, ever smoked, kcals of physical activity/week, body mass index, and initial MRI grade on white matter or ventricle as appropriate.

TABLE 5 Association between neighborhood greenspace–neighborhood income measure and dichotomous MRI outcomes.

MRI outcome (worsening from initial to follow-up MRI)	Neighborhood greenspace–neighborhood income measure[a]	Partially adjusted model[b]		Fully adjusted model[c]	
		OR (95% CI)	*P*-value	OR (95% CI)	*P*-value
White matter grade	Lower greenspace, lower income	1.60 (1.12–2.30)	0.01	1.73 (1.19–2.51)	0.004
	Lower greenspace, higher income	1.11 (0.70–1.78)	0.65	1.17 (0.72–1.89)	0.53
	Higher greenspace, lower income	1.08 (0.66–1.78)	0.75	1.16 (0.70–1.93)	0.57
Ventricle grade	Lower greenspace, lower income	0.65 (0.41–1.01)	0.06	0.77 (0.51–1.16)	0.21
	Lower greenspace, higher income	0.60 (0.38–0.97)	0.04	0.71 (0.45–1.12)	0.14
	Higher greenspace, lower income	1.16 (0.70–1.94)	0.56	0.92 (0.56–1.52)	0.75

Abbreviations: CI, confidence interval; MRI, magnetic resonance imaging; OR, odds ratio.
[a]Greenspace dichotomized at median of 37%; neighborhood median household income dichotomized at median of $56,267/year; reference group = higher greenspace-higher income neighborhood.
[b]Controlling for age, sex, racialized group (non-White vs. White), marital status, income, education, population density, site/clinic, and time between first and second MRI (white matter grade model: $n = 1180$; ventricle grade model: $n = 1180$).
[c]Additionally controlling for diabetes, arthritis, hypertension, cardiovascular disease, cerebrovascular disease, ever smoked, kcals of physical activity/week, body mass index, and initial MRI white matter and ventricle grades (white matter grade model: $n = 1177$; ventricle grade model: $n = 1177$).

forest × neighborhood income interaction terms were not significant in fully adjusted models ($P > 0.05$, data not shown).

4 | DISCUSSION

Individuals in lower greenspace–lower income neighborhoods (vs. higher greenspace–higher income) were more likely to experience a 5-year white matter grade worsening after controlling for important confounders including individual SES. Null associations for the other neighborhood greenspace–income categories may suggest that living in neighborhoods with either lower median incomes or less greenspace alone is insufficient to be associated with worsening white matter grade. Overall, the combined association of lower neighborhood income and lower greenspace with worsening white matter grade should be verified in future studies.

While no known prior studies have examined combined effects of neighborhood greenspace and NSES on MRI outcomes, studies focused on these neighborhood factors individually inform our interpretations. Cross-sectional studies found that greater neighborhood disadvantage was associated with cortical thinning in AD ROI and lower hippocampal and total brain volumes in cognitively unimpaired middle- to older-age adults.[14,15] A previous CHS study found greater neighborhood greenspace was borderline associated with lower ventricle grade score.[21] Greater neighborhood greenness was associated with greater amygdala integrity[25] and greater cortical thickness in middle-age to older adults,[22–24] and multiple gray and white matter regional volumes among children and middle-age to older adults.[26,27] These studies suggest beneficial associations for both greater NSES and greenspace on structural brain health measures. While previous studies used more specific brain imaging measures to potentially pinpoint causal relationships, their cross-sectional approach limits causal inference. A unique strength of this study is the demonstration of associations between neighborhood greenspace and NSES and subsequent white matter grade worsening.

We found no associations with worsening ventricle grade, although a previous CHS study found a borderline association between greater neighborhood greenspace and lower ventricle grade score.[21] Development of WMH and ventricular expansion were only moderately associated in prior work, suggesting that mechanisms leading to their development do not completely overlap.[51] Causal mechanisms relating greenspace and neighborhood income to worsening white matter need elucidation but could relate to factors previously associated with neighborhood factors and WMH, including hypertension. If higher greenspace–higher income neighborhoods protect against future worsening of WMH, the benefit may eventually extend to reduce stroke and dementia risk, given prior associations between WMH and greater risk of these conditions.[52] Studies with extended longitudinal measurements could investigate neighborhood greenspace–NSES and WMH associations as a mediating pathway to stroke and dementia development.

Findings for lower income–lower greenspace neighborhoods could represent a few scenarios. Those neighborhoods may be capturing areas with lower quality greenspaces as may be found in low-income neighborhoods. Preliminary studies suggest the importance of greenspace type and quality. For example, having more tree canopy (vs. open grassland) has been associated with lower odds of subjective cognitive complaints and greater odds of self-rated excellent memory.[53] Greenspace quality may be more important than quantity and should be investigated using cohorts with greenspace quality data. However, given frequent associations between NSES and both ADRD risk factors (e.g., diabetes and hypertension) and outcomes such as stroke and ADRD,[14,15,54] poor greenspace quality is unlikely to be the sole explanation for our findings for lower greenspace–lower income neighborhoods. Another possibility is that higher greenspace–higher income neighborhoods represent the most advantaged, and conversely, lower greenspace–lower income neighborhoods represent the most disadvantaged neighborhoods. Considered separately, neighborhood income but not greenspace was associated with worsening white matter grade, suggesting that our neighborhood greenspace–income variable may be a proxy capturing greater variation in NSES than neighborhood income alone.[55] Nonetheless, future work needs to tease apart the relative importance of neighborhood greenspace amount and quality and NSES to brain health changes over time in older adults. This is important given the rapidly growing number of studies demonstrating beneficial associations between greenspace and brain health (e.g., 74% of 56 studies in a rapid review[56]), and the limited number investigating potential causal pathways responsible for observed beneficial associations (e.g., greater social and physical activity and lower air pollution exposure).

Study strengths include the use of a population-based cohort, a combined measure of neighborhood greenspace and NSES, and longitudinal MRI. A number of limitations must be noted. Our greenspace measure did not account for accumulated exposure over time/the life course, which could be investigated using cohorts with residential history data. MRI outcomes were measured over two time points, and more frequent outcome measurement might result in different findings in future research. We could not examine neighborhood greenness (e.g., using normalized difference vegetation index) or greenspace types such as parks versus tree canopy. While post hoc analyses evaluated percentage forest, it could not be compared to other greenspace types due to NLCD limitations, which will be important in future studies. In addition, we did not capture actual exposure such as hours spent in greenspace/week. Although our sensitivity analyses compared results using neighborhood income to a composite NSES measure constructed from four Census measures, new studies would benefit from the use of established NSES indices like the ADI. Neighborhood type (e.g., single family homes vs. retirement village) may relate to SES and thus is important to incorporate in future studies. In this study, we aimed to investigate whether living in neighborhoods differing in amount of greenspace and median income at baseline are temporally followed by longitudinal change in MRI outcomes, but future studies might examine associations between changes in neighborhood percentage greenspace and longitudinal change in MRI outcomes. Inadequate statistical power may explain null findings for the neighborhood greenspace × neighborhood income interaction term and for the other neighborhood greenspace–income strata. However, power is often limited to detect interactions and the importance of understanding stratum-specific effects and not simply focusing on interaction term significance is increasingly emphasized.[57] Although we accounted for hypertension in our models, we lacked information on adequate control of hypertension through medication, which may impact change in white matter grade. White matter and ventricle grade are useful longitudinal measures of white matter damage and brain atrophy but were the only two longitudinal brain imaging measures readily available from CHS and were not measured quantitatively. Imaging measures such as regional volumes (e.g., hippocampal volumes) as well as cortical thickness and integrity of AD ROI may be fruitful, more specific targets related to ADRD for future research. We restricted to those with MRI and greenspace data, which may have resulted in selection bias and limited generalizability. We know that CHS participants completing initial and follow-up MRIs differed from the overall sample (e.g., had higher SES and less heart disease than those with only initial MRI).[37] Also, pooling data across the four CHS sites limits an understanding of site-specific neighborhood characteristics related to greenspace and NSES that may be associated with brain aging.

Future studies would benefit from a city-specific investigation of neighborhood greenspace–NSES and brain health associations, potentially using mixed methods to incorporate residents' perspectives that can illuminate lived experiences and community resource needs.

A significant limitation is the sample's lack of racial/ethnic diversity. This limited examination of associations within specific groups, which will be critical in other cohorts with sufficient sample sizes of minoritized participants. Historic (e.g., redlining) and persistent structural inequities resulting in longstanding residential segregation have led to poorer neighborhood environments, including greenspaces and NSES, among minoritized individuals. Additional studies should verify the impacts of policies and structural factors on neighborhood and ADRD-related outcome disparities between populations, as well as determine key mediators on the causal pathway for neighborhood-brain imaging associations (e.g., stress, physical activity, and social isolation), particularly among minoritized groups.

5 | CONCLUSION

Living in neighborhoods with lower NSES and less greenspace may be associated with greater white matter damage over time among older adults, which may increase stroke and dementia risk. Provision of new greenspaces to neighborhoods with inadequate access or poor-quality greenspaces may improve lifestyle behaviors and exposures throughout the life course and subsequently reduce ADRD risk. However, evidence remains limited that supports specific built environments, such as greenspaces, for ADRD prevention. While provision of resources and high-quality greenspaces to historically disadvantaged neighborhoods may be a strategy to help maintain brain health and reduce disparities, our results are preliminary and must be replicated before informing such policies. Findings and limitations from this study provide avenues for future research, such as studies focused on minoritized groups/neighborhoods, using mixed methods, and investigating the impact of greenspace quality or established NSES measures on longitudinal brain imaging outcomes.

ACKNOWLEDGMENTS

Dr. Besser is supported by NIH/NIA award K01AG063895, NIH/NIA award R21 AG075291, and the Alzheimer's Association (AARG-21-850963). Yvonne L. Michael (NIH/NIA, 3R01AG049970-04S1), Jana A Hirsch (NIH/NIA, R01AG072634), James Galvin (NIA/NIH Grants R01AG040211, R01NS101483). The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health. This research was supported by contracts HHSN268201200036C, HHSN268200800007C, HHSN268201800001C, N01HC55222, N01HC85079, N01HC85080, N01HC85081, N01HC85082, N01HC85083, N01HC85086, 75N92021D00006, and grants U01HL080295 and U01HL130114 from the National Heart, Lung, and Blood Institute (NHLBI), with additional contribution from the National Institute of Neurological Disorders and Stroke (NINDS). Additional support was provided by R01AG023629 from the National Institute on Aging (NIA). A full list of principal CHS investigators and institutions can be found at CHS-NHLBI.org. Characterization of geographic units was supported by the National Institute on Aging (grants 1R01AG049970, 3R01AG049970-04S1), Commonwealth Universal Research Enhancement (C.U.R.E) program funded by the Pennsylvania Department of Health—2015 Formula award—SAP #4100072543, the Urban Health Collaborative at Drexel University, and the Built Environment and Health Research Group at Columbia University.

CONFLICT OF INTEREST STATEMENT

Lilah Besser, Gina Lovasi, Joyce Jimenez Zambrano, Simone Camacho, Devi Dhanekula, Yvonne L. Michael, Parveen Garg, Jana Hirsch, David Siscovick, Philip M. Hurvitz, Mary Lou Biggs, James Galvin, and Traci Bartz have no conflicts of interest. Will Longstreth serves as a co-PI for the NIH-funded ARCADIA trial, which receives in-kind study drug from the BMS-Pfizer Alliance and ancillary funding from Roche Diagnostics. Author disclosures are available in the supporting information.

CONSENT STATEMENT

The institutional review board at each CHS site/center approved the study and all participants signed an informed consent.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Besser LM, Lovasi GS, Zambrano JJ, et al. Neighborhood greenspace and neighborhood income associated with white matter grade worsening: Cardiovascular Health Study. *Alzheimer's Dement*. 2023;15:e12484. https://doi.org/10.1002/dad2.12484